NASA TECHNICAL MEMORANDUM

NASA TM X-2183

NASA TM X-2183

TWO-DIMENSIONAL CASCADE TEST OF A JET-FLAP TURBINE ROTOR BLADE

by Stanley M. Nosek and John F. Kline

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1971

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2183		

4. Title and Subtitle	5. Report Date
TWO-DIMENSIONAL CASCADE TEST OF A JET-FLAP TURBINE ROTOR BLADE	February 1971
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Stanley M. Nosek and John F. Kline	E-5989
	10. Work Unit No.
9. Performing Organization Name and Address	720-03
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A jet-flap turbine blade was tested in a two-dimensional cascade of six blades to study the effectiveness of the concept as a boundary-layer control device and as a variable-area device. Principal measurements were surveys of blade surface static pressure and blade exit total pressure, static pressure, and flow angle at midspan. Data were taken at constant pressure ratio for jet flows from 0 to 4 percent of primary flow. Results are presented in terms of primary flow, blade surface pressure distribution, blade specific force, kinetic energy loss coefficient, total-pressure loss, and exit flow angle.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Turbines Cascades Jet-flap blades	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	18	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

TWO-DIMENSIONAL CASCADE TEST OF A JET-FLAP TURBINE ROTOR BLADE

by Stanley M. Nosek and John F. Kline

Lewis Research Center

SUMMARY

A jet-flap turbine blade was tested in a two-dimensional cascade to study the effectiveness of the concept as a boundary-layer control device and as a variable-area device. The blades were instrumented with static-pressure taps to determine pressure forces on the blades. In addition, surveys were made across the exit of the blades of total pressure, static pressure, and flow angle to define flow conditions leaving the blades. Jet flow rates from 0 to 4 percent of primary flow were used in the study. Flow separation was eliminated with no change in primary flow at about $1\frac{1}{2}$ percent jet flow. At this condition, the tangential force per unit of primary flow was a maximum. As additional jet flow was added, the jet acted as a variable-area device and reduced the flow rate. For example, at 4 percent jet flow, the primary flow was reduced a total of 10 percent. Design primary flow rate was obtained with a jet flow rate of 3.1 percent. At this condition, the tangential force per unit of primary flow was 6 percent below the design value.

INTRODUCTION

The Lewis Research Center is experimentally investigating the potential of two new blade design concepts, tandem blades and jet-flap blades, for achieving higher loading on turbine blades. Under contract, preliminary tests have been made with a single stage low reaction turbine and with a three-dimensional sector cascade. The results are presented in references 1 and 2. Investigations are continuing with the single stage turbine.

At the Lewis Research Center, investigations are being made with a two-dimensional cascade of six blades. The purpose here is to study the concepts on a more fundamental basis. So far, blades designed to the mean section profile of the rotor

blades tested in the turbine (ref. 1) have been studied. In reference 3 the results with the tandem blades were presented. In this report the results with the jet-flap blades are presented.

In the jet-flap concept, a jet of air (possibly coolant) from inside the blade is ejected into the main stream near the trailing edge, to form what is essentially an aerodynamic flap. The jet-flap deflects the primary stream and increases the velocity on the aft portion of the suction surface. Separation is thereby avoided and a higher loading can be obtained without excessive losses. Also, since it deflects the stream, the jet flap could serve as a variable-area device.

The objective in this investigation was to study the effectiveness of the jet flap in accomplishing both of these features; that is, as a boundary-layer control device and as a variable-area device.

The principal measurements were blade surface static pressure and tangential surveys of total pressure, static pressure, and flow angle at the blade exit. These data were taken at design inlet flow angle and constant pressure ratio over a range of jet flows from 0 to 4 percent of primary flow. The results are presented in terms of channel flow, blade surface pressure distribution, blade force per unit channel flow, kinetic energy loss coefficient, total-pressure loss, and exit flow angle.

SYMBOLS

a distance along axial chord from blade leading edge, in. (cm)

c_a blade axial chord, in. (cm)

$\bar{e}$ thermodynamic kinetic energy loss coefficient, $1 - \dfrac{w_M V_M^2}{w_P (V_{M,id})_P^2 + w_J (V_{M,id})_J^2}$

$\bar{e}^*$ primary kinetic energy loss coefficient, $1 - \dfrac{w_M V_M^2}{w_P (V_{M,id})_P^2}$

F tangential force on blade per inch (cm) of span indicated by pressure profile at midspan, lbf (N)

p pressure

s tangential blade spacing, in. (cm)

t tangential distance from blade trailing edge, in. (cm)

V velocity

w flow rate per inch (cm) of span, lb/sec (kg/sec)

$\sqrt{\theta_{cr}}$ ratio of critical velocity at blade inlet to critical velocity of U. S. standard sea-level air

β flow angle, deg from axial

Subscripts:

cr condition at Mach 1

id ideal, of isentropic process

J jet flow

M "uniform flow" conditions computed from station 2 survey data

P primary flow

1 blade inlet station

2 blade exit survey station

Superscript:

' total state condition

EQUIPMENT AND PROCEDURE

The equipment for this investigation consisted of a two-dimensional cascade of jet-flap blades, a cascade tunnel, a secondary air supply for the jet, and instrumentation.

Blade and Cascade

The blades were machined to the coordinates proposed in reference 4 for the mean section of a jet-flap rotor blade. The profile was accurate to ±0.003 inch (0.0076 cm) after the surface was finished to about 32 microinches (81×10^{-6} cm) rms.

The blades were hollowed out as indicated in figure 1 to provide a flow passage to the jet slot from one end. Struts 1/16 inch (0.159 cm) thick were placed 1 inch (2.54 cm) apart spanwise to bridge the slot for structural purposes and to aline the flow (fig. 1). The slot was cut at the design angle (33°) along the complete 5-inch (12.7-cm) active portion of the blade.

The cascade was formed with six blades set at design spacing and angle (fig. 1). The axial solidity of the cascade is 1.80.

The velocities and angles shown at the channel inlet and channel exit in figure 1 are from the three-dimensional design (ref. 4) for the mean blade section.

Cascade Tunnel

The cascade of blades was mounted in a 5-inch- (12.7-cm-) wide cascade tunnel at the design inlet flow angle (48.4° from axial). This suckdown tunnel, fully described and illustrated in reference 3, has transparent side walls, adjustable inlet guide walls, and suction slots for boundary-layer removal in the side walls just ahead of the blades (fig. 2). The inlet guide walls were alined with the leading edges of the extreme blades of the cascade and set to contact them. The exit guide walls were set about 3 inches (7.62 cm) outside the trailing edge of the extreme blades so that the cascade flow would not be deflected.

Jet Air Supply System

Jet air was supplied to one end of the hollow blades through a dual inlet manifold (fig. 2(a)) into which all six blades projected in a similar manner. Flow distribution was assumed to be equal. Dry air was supplied to the manifold through an ASME flat plate orifice.

Instrumentation

Surface static-pressure taps were installed at midspan on the facing surfaces of the two center blades of the cascade and on both tunnel sidewalls at the center channel inlet (fig. 1). The pressure sensed by these 0.020-inch- (0.051-cm-) diameter taps was scaled with mercury manometers and recorded by photographing the manometer banks.

Blade Exit Surveys

The total pressure, static pressure, and flow angle at the channel exit were surveyed simultaneously with the rake shown in figure 3. This rake has two total-pressure probes, a 15° wedge static-pressure probe, and a flow angle sensing probe. The total-pressure probes were formed from 0.020-inch- (0.051-cm-) diameter, 0.0025-inch- (0.0064-cm-) wall tubing flattened to a 0.005-inch (0.013-cm) inner dimension at the tip. The flow angle probe was of the two-tube 45° scarf type. The exact dimensions of the rake are given in figure 3(a). The orientation of the probes on the rake is further clarified in figure 3(b).

The rake was calibrated throughout the range of conditions encountered in the test, and readings from each probe were corrected accordingly.

The positioning of the rake in the cascade tunnel is shown in figure 2(b). The probe tips were located at midspan 0.43 inch (1.09 cm) axially downstream from the blade trailing edges and were traversed parallel to the plane of the trailing edges (fig. 1). The rake angle was fixed throughout each survey. Traverse speed was about 1 inch per minute (2.54 cm/min).

Probe pressures were measured with strain-gage pressure transducers and recorded as a function of traverse position on x, y-recorders.

One pressure tap was installed inside each of the two center blades to sense the total pressure of the jet air at the slot inlet.

Thermocouples were positioned at the cascade inlet and inside the jet air manifold to sense air temperature.

Procedure

The cascade was tested over a range of jet to primary flow ratios with the inlet total- to exit static-pressure ratio at a constant value. The pressure ratio selected was that which would result in an exit velocity close to design at design inlet velocity (fig. 1).

RESULTS AND DISCUSSION

In this section the effect of the jet upon blade performance is presented in terms of primary flow rate, pressure distribution on the surface of the blade, flow specific force, blade exit survey profiles, total-pressure loss, kinetic energy loss, and turning of the flow.

Between 2 and 3 percent jet flow a hysteresis effect was noted. One set of points was recorded as jet flow was increased from below 2 percent; the other set as jet flow was reduced from above 3 percent. Since this could be characteristic of the tunnel rather than the blades, the effect will be treated as data scatter.

Design values presented herein are based on the velocity diagram of figure 1 and the pressures of reference 4 assuming two-dimensional flow.

Primary Flow Rate

Primary flow was essentially unaffected as jet flow was increased from 0 to $1\frac{1}{2}$ percent (fig. 4). As additional jet flow was added, the jet acted as a variable-area device and reduced the flow rate. At 4 percent jet flow, the primary flow was reduced a total of 10 percent. The design value of primary flow was obtained with a jet flow of about 3.1 percent.

Primary flow was computed from the wall static-pressure taps across the channel inlet, assuming the inlet flow to be parallel to the tunnel guide walls. As a check on the validity of this assumption and also upon the two-dimensionality of the cascade, primary flow was deduced by subtracting jet flow from total flow (integrated from the downstream survey). At jet flows above 2 percent they agreed within ±2 percent. At lower jet flows the deduced flow was up to 6 percent higher, indicating a reduction in flow area at the channel exit, possibly due to secondary flow at the walls.

Blade Surface Pressure Distribution

Blade surface pressures at several values of jet flow are shown in figure 5. To clarify the presentation, curves are drawn through significant sets only.

Without jet flow, the pressure on the suction surface increases abruptly between chord fractions of 0.6 and 0.75 and remains constant from there aft, indicating flow separation. A jet flow of 1.40 percent was required to produce a significant change - a general lowering of pressures between 0.5 and 0.85 chord fractions. The resultant profile indicates that separation has been delayed appreciably; the diffusion ramp is about 0.1 chord fraction farther downstream, but the slope is unchanged. Increasing jet flow to 1.93 percent lowered pressures in the region between 0.7 and 0.85 chord fractions, making the diffusion ramp less steep and therefore even less indicative of separation.

Further increases in jet flow produced no appreciable change in the location of the diffusion profile. The slope was reduced somewhat, but this was due to the general rise in pressure on all blade surfaces as primary flow decreased.

Blade Loading

The effect of jet flow upon blade specific force (blade force per unit primary flow) is shown in figure 6. Specific force rises as jet flow is increased from 0 to 1.9 percent, since the blade pressure force is increasing while primary flow is constant. As jet flow

is increased further, specific force decreases gradually. Primary flow is decreasing, but blade force is decreasing faster.

At design primary flow (3.1 percent jet flow) the specific force was about 6 percent below the design value of 33.8 pound force - second per pound mass (331.5 N-sec/kg).

The blade force was computed from the blade surface pressure distribution. The pressure surface diagram was closed by assuming the pressure to be constant from the last tap to the downstream edge of the jet, and then to vary linearly to the trailing edge tap (see fig. 5).

Exit Surveys

Profiles of total pressure, static pressure, and flow angle across the center channel and the two adjacent wakes at several jet flow rates are shown in figure 7.

Without jet flow the wake defined by the total-pressure profile (fig. 7(a)) is deep and wide, indicating separation. The flow angle varies almost 10° across the free stream (fig. 7(b)). At 1.40 percent jet flow the wake is shallower and narrower. The suction surface of the wake has shifted toward the blade suction surface, indicating that the flow has been diverted by the jet. The flow angle variation across the free stream has decreased to 5°. As jet flow is increased further, the wake depth continues to decrease. The wake width, however, begins to increase on the pressure surface side, where the jet is mixing with the free stream. The suction surface remains stationary, indicating that the flow was attached at 1.40 percent jet flow, and probably separated at zero jet flow.

The static-pressure profile (fig. 7(a)) is relatively flat and shows no significant trends.

Kinetic Energy Loss Coefficient

The effect of jet flow on kinetic energy loss is shown in figure 8. The thermodynamic loss coefficient, which charges the ideal energy of the jet to the process, is shown in figure 8(a). The minimum loss of about 9 percent occurred at a jet flow of about 2 percent. At design inlet flow (3.1 percent jet flow) the loss was about 10 percent.

The primary air loss coefficient (fig. 8(b)) does not charge the ideal energy of the jet to the process. Consequently, the value decreases continuously as jet flow is increased. It is particularly applicable for engine cycle analysis when cooling air is discharged, as in a jet flap.

It should be noted that these coefficients are based on uniform flow conditions at the blade exit, and that the procedure for calculating these conditions implies kinetic energy loss which is representative of the mixing losses that would actually occur. This implied mixing loss is almost half of the total loss when channel flow is separated (no jet flow), but decreases to become less than one-tenth of the total loss when channel flow is attached (jet flow above 1.4 percent).

Total-Pressure Loss

The overall total-pressure loss from blade inlet to blade exit "uniform flow" conditions decreases continuously as jet flow is increased (fig. 9).

At design primary flow (3.1 percent jet flow) the loss is about 3 percent. The "design" loss for the three-dimensional analysis is 9.5 percent. This cannot be used for comparison, since it includes shared blade end losses.

Exit Flow Angle

The effect of the jet upon the flow angle downstream from the blades is shown in figure 10. Flow angle increases continually with jet flow. At design primary flow (3.1 percent jet flow) the flow angle is about 4° larger than design, primarily because of the higher than design exit static pressure.

SUMMARY OF RESULTS

A jet-flap turbine blade was tested in a two-dimensional cascade to study the effectiveness of the concept as a boundary-layer control device and as a variable-area device. The blades were instrumented with static-pressure taps to determine pressure forces on the blades. In addition, surveys were made across the exit of the blades of total pressure, static pressure, and flow angle to define flow conditions leaving the blades. Jet flow rates from 0 to 4 percent of primary flow were used in the study. The following results were found:

1. Flow separation from the suction surface of the blade was eliminated with the addition of about $1\frac{1}{2}$ percent jet flow. At this condition, both the tangential force (from blade static-pressure measurements) and the specific tangential force (per unit of primary air flow) were maximum.

2. Design primary air inlet flow conditions were attained at a jet flow of 3.1 percent. At this condition, the experimentally determined specific tangential force on the blade was 6 percent below the design value. Also, the flow was turned about 4° more than design.

3. Exit surveys at the midspan blade section indicated a minimum thermodynamic loss in kinetic energy of about 9 percent at a jet flow of 2 percent. At design primary flow (3.1 percent jet flow) the loss was about 10 percent.

4. Jet flows up to $1\frac{1}{2}$ percent had no effect on primary flow rate. Above this value, the jet was effective as a variable flow device. For example, when the jet flow was increased from $1\frac{1}{2}$ to 4 percent, the primary flow decreased 10 percent.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 4, 1970,
720-03.

REFERENCES

1. Lueders, H. G.; and Roelke, R. J.: Some Experimental Results of Two Concepts Designed to Increase Turbine Blade Loading. Paper 69-WA/GT-1, ASME, Nov. 1969.
2. Bettner, James L.; and Nosek, Stanley M.: Summary of Tests on Two Highly Loaded Turbine Blade Concepts in Three-Dimensional Cascade Sector. Paper 69-WA/GT-5, ASME, Nov. 1969.
3. Nosek, Stanley M.; and Kline, John F.: Two-Dimensional Cascade Investigation of a Turbine Tandem Blade Design. NASA TM X-1836, 1969.
4. Lueders, H. G.: Experimental Investigation of Advanced Concepts to Increase Turbine Blade Loading. I - Analysis and Design. NASA CR-735, 1967.

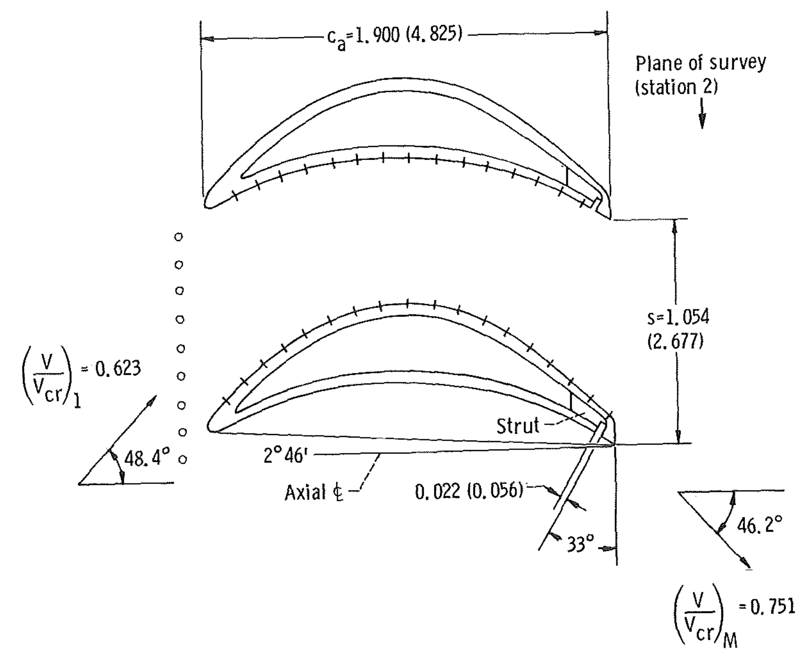
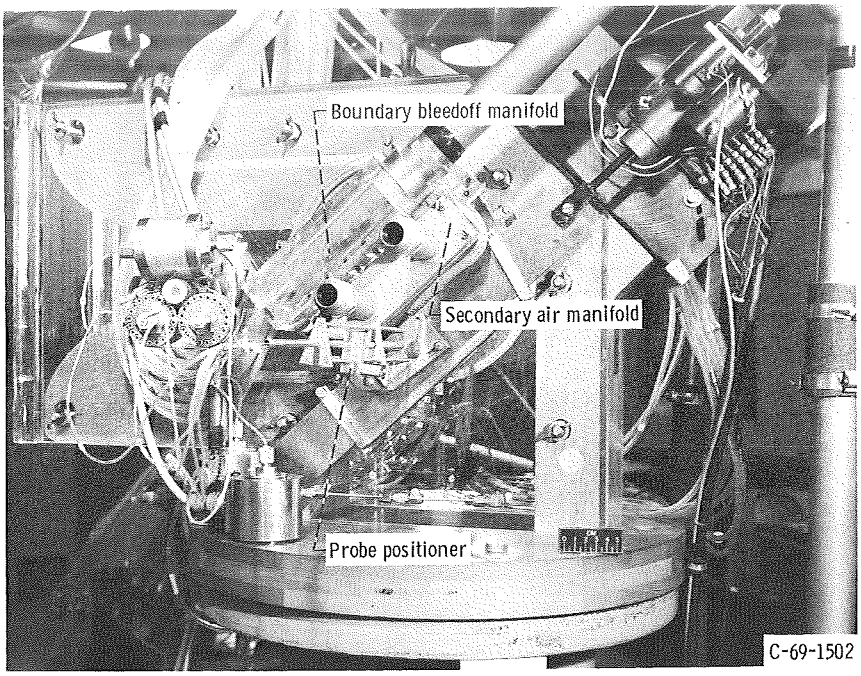
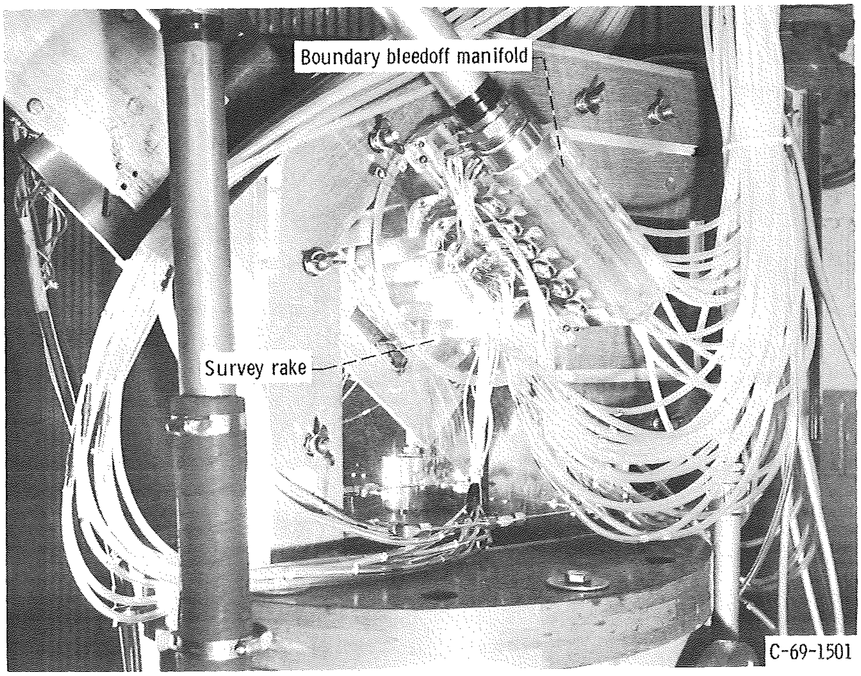


Figure 1. - Jet-flap blade geometry and velocity diagrams. Location of blade surface taps is indicated by ticks. (Dimensions are in inches (cm).)

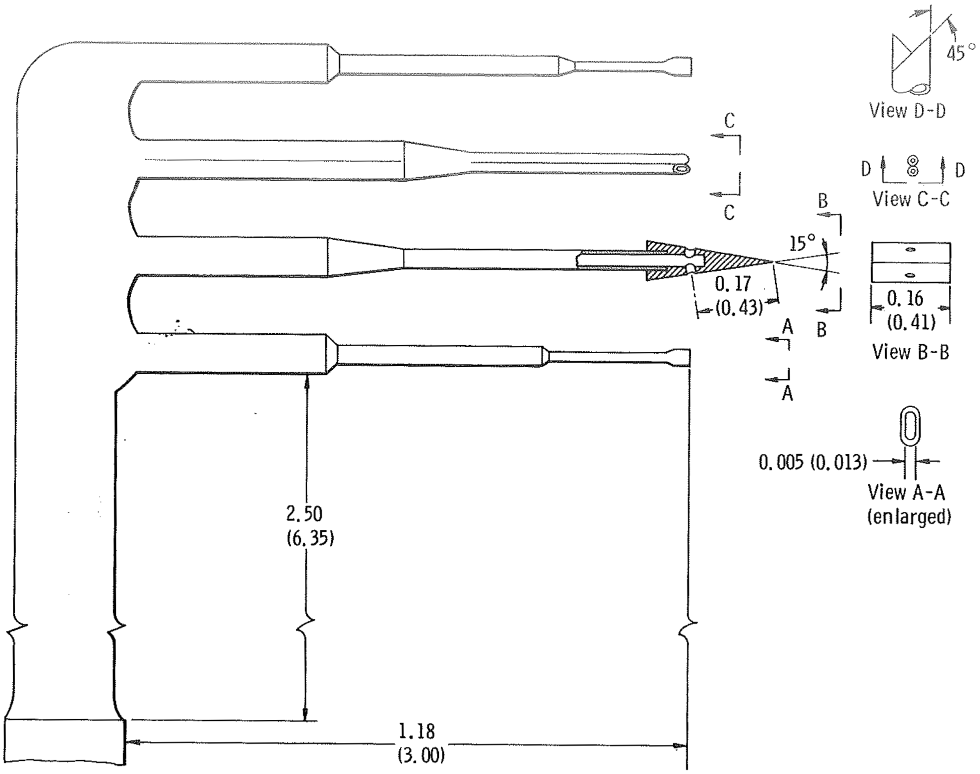


(a) Probe positioner and secondary air manifold.

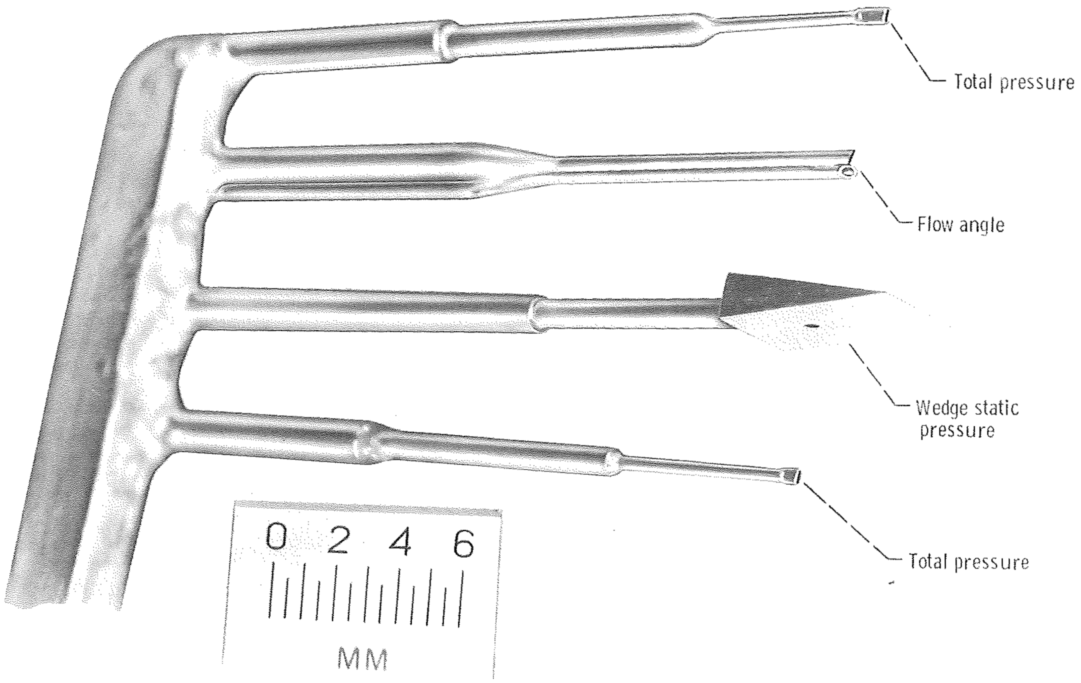


(b) Rake orientation to blades.

Figure 2. - Cascade tunnel.



(a) Schematic diagram. (Dimensions are in inches (cm).)



(b) Overall view.

Figure 3. - Survey rake.

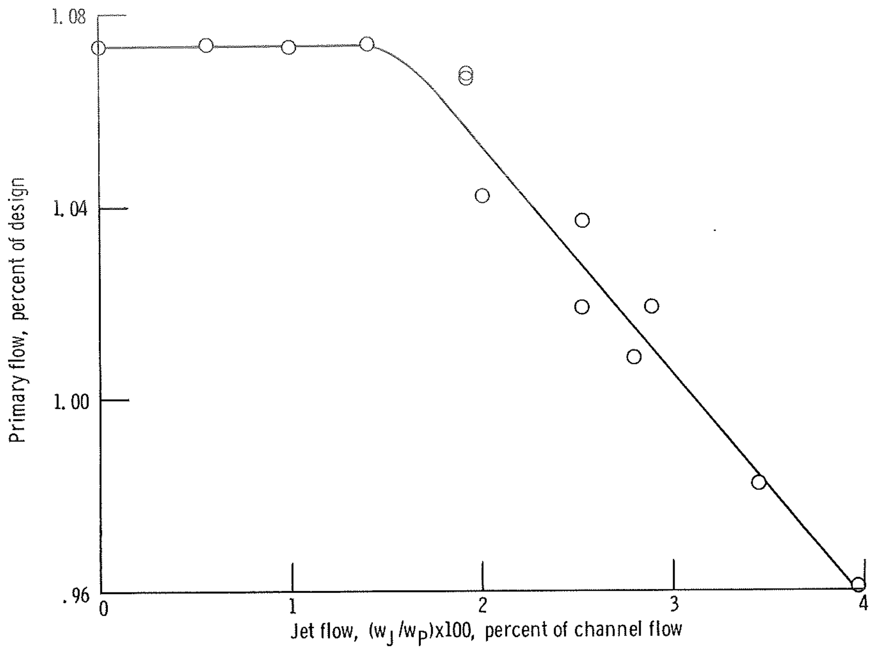


Figure 4. - Primary flow as function of jet flow.

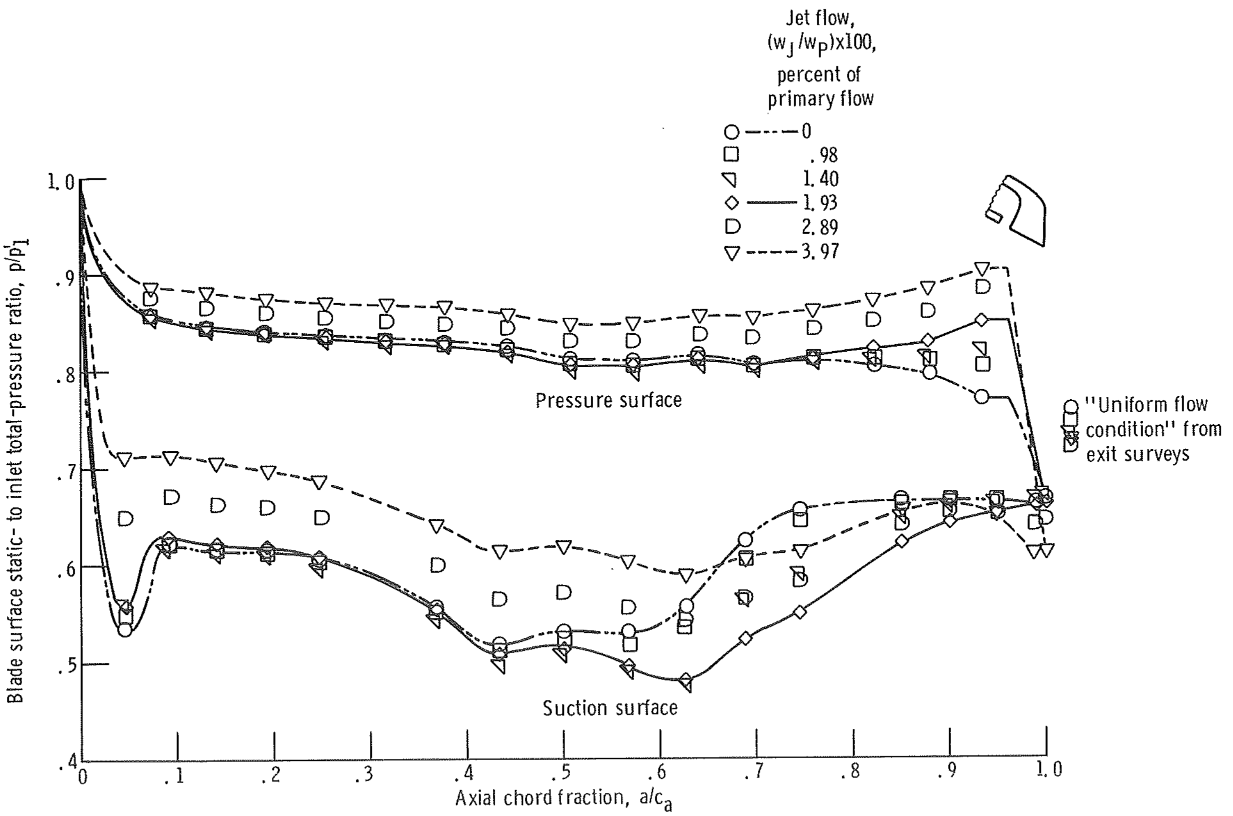


Figure 5. - Static-pressure distribution on blade surface.

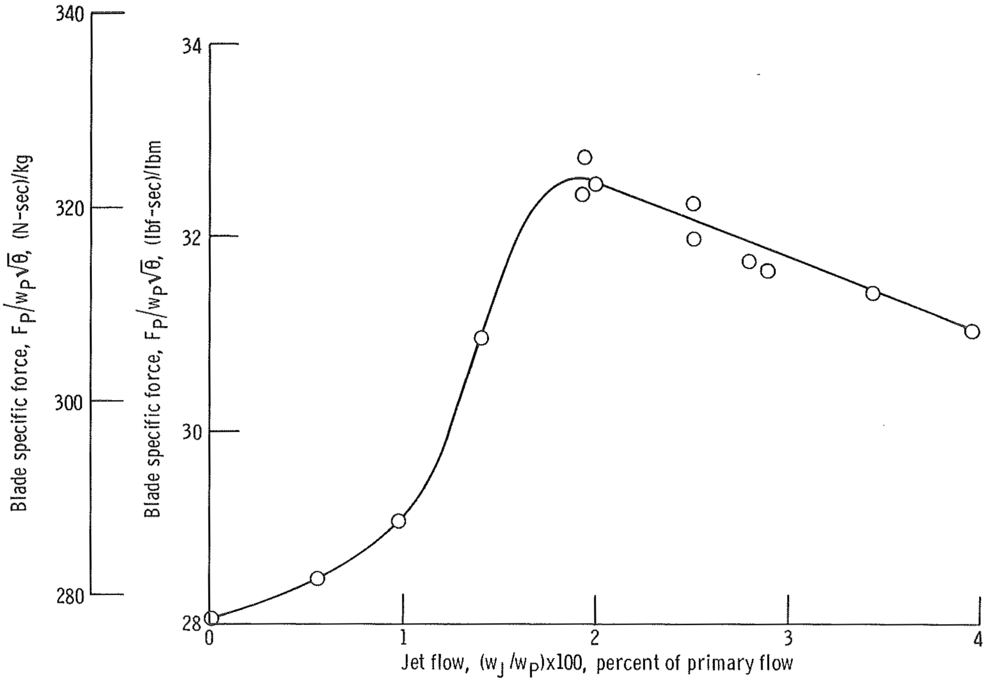
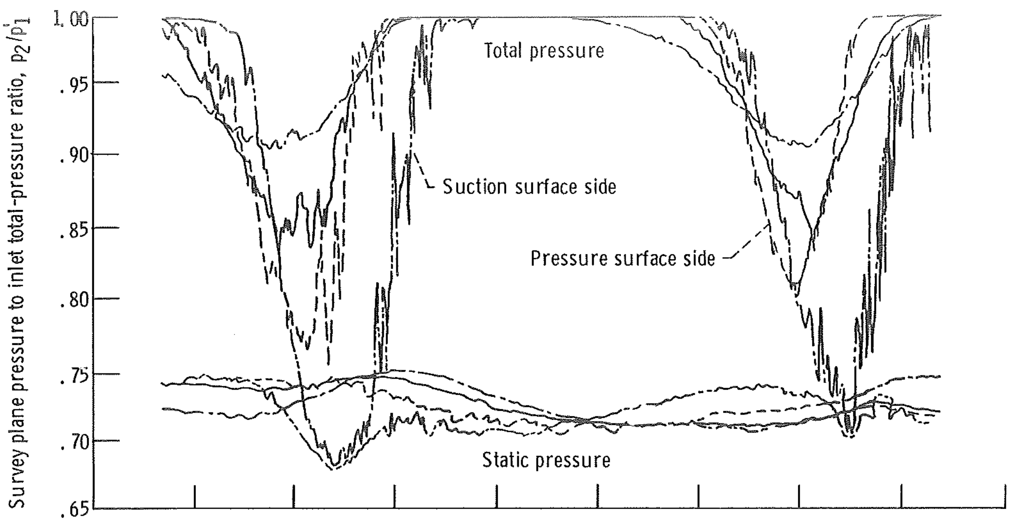
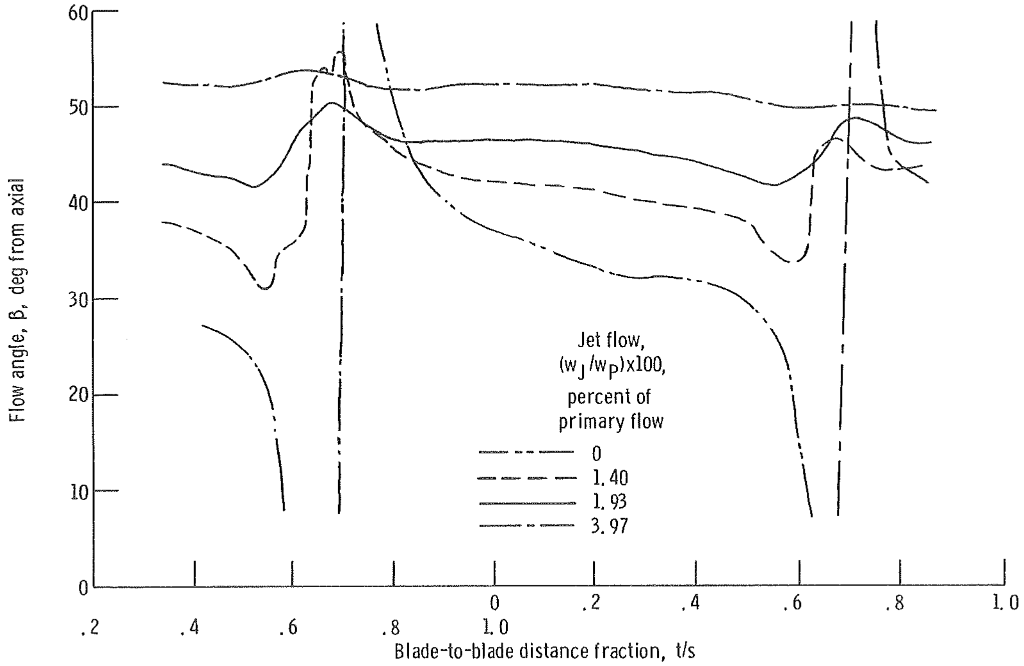


Figure 6. - Blade specific force as function of jet flow.

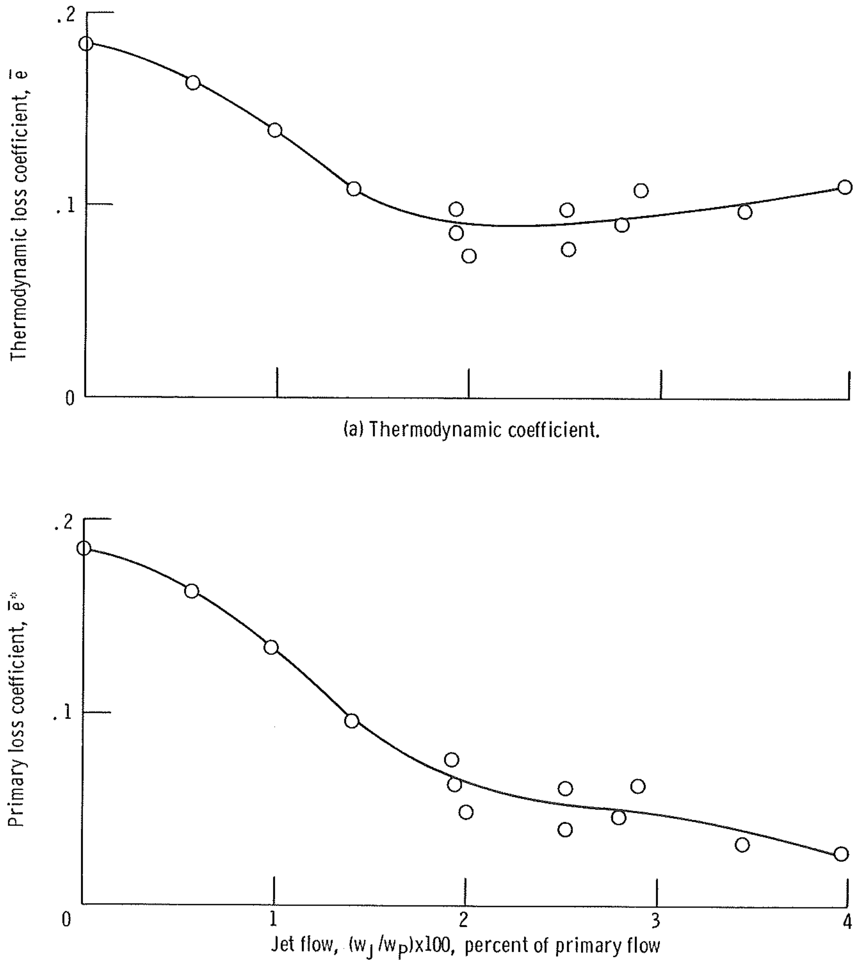


(a) Pressure.



(b) Flow angle.

Figure 7. - Blade exit pressure and flow angle profile variation with jet flow.



(a) Thermodynamic coefficient.

(b) Primary coefficient.

Figure 8. - Kinetic energy loss as function of percent jet flow.

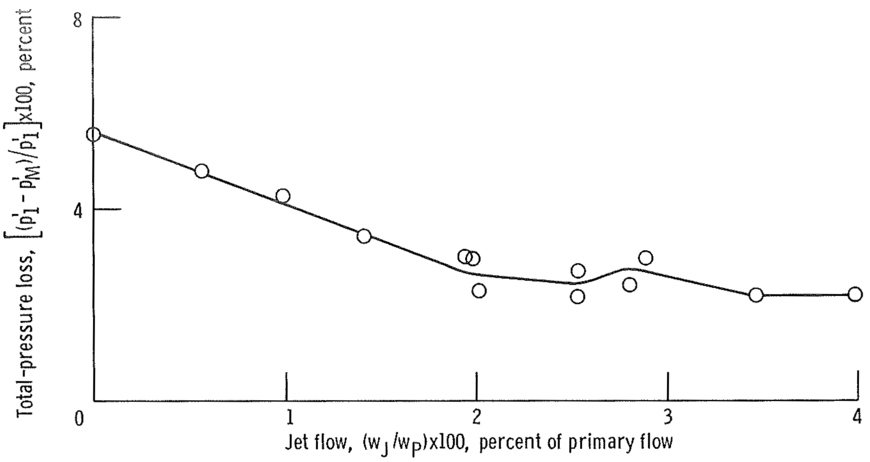


Figure 9. - Total-pressure loss variation with jet flow.

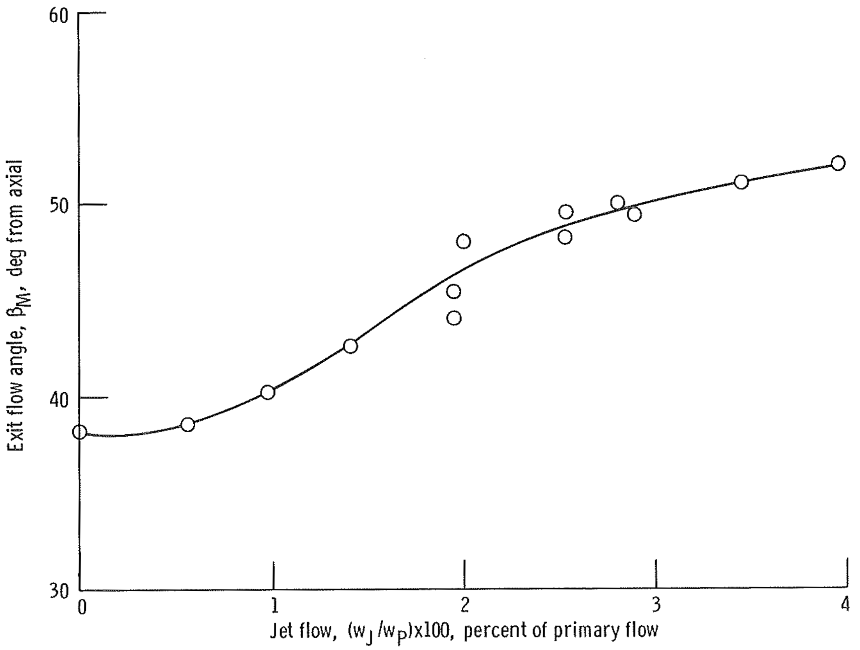


Figure 10. - Blade exit average flow angle variation with percent jet flow.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546